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BASSOON IV (U)

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RESEARCH PAPER P-164

BASSOON IV (U)
PROPOSED WISCONSIN E.L.F. TRANSMITTER ~~(S)~~

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Nicholas Christofilos

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RESEARCH PAPER P-164

BASSOON IV (U)
PROPOSED WISCONSIN E.L.F. TRANSMITTER ~~(S)~~

Nicholas Christofilos

January 5, 1965
(Revised April 27, 1965)

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BASSOON IV (U)
PROPOSED WISCONSIN E.L.F. TRANSMITTER ~~(S)~~

Nicholas Christofilos*

I. INTRODUCTION

Polaris submarines are now tethered to the surface of the ocean by their receiving antennae. Their superb speed, maneuverability, and concealment are degraded by their need to trail a buoy or floating wire in order to maintain contact with V.L.F. or other transmitting stations.

It is possible, however, to relieve the submarine of such encumbrances. By using an unconventionally low transmitter frequency in the E.L.F. range -- 25 to 100 cps -- the submarine can receive, through a hull-mounted receiving antenna, at several hundred feet below the surface and while traveling at 10 to 20 knots.

This E.L.F. communication system has the further advantage as a National Survivable System by its resistance to nuclear attack. The transmitting elements, as now conceived, can be built in such a hardened, dispersed fashion that a missile force the size of the projected Polaris force on station could not destroy completely its ability to function.

*University of California, Livermore, California

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Another unique property of an E.L. F. communication system is its invulnerability to jamming. Not only it is <u>not</u> possible to build <u>mobile</u> E.L.F. transmitters (even on ships), but it is impossible to build them at any particularly desired place on land. Special geological conditions are required -- the existence of extended areas of Pre-Cambrian rocks to allow the radiation of a substantial amount of power within reasonable cost. From geological maps one can predict the locations in the Eurasian continent which are suitable for an E.L.F. transmitter. The combination of a directive receiving antenna, the proper selection of our operational areas in the perimeter of the Eurasian continent, and an inherent anti-jamming capability of the E.L.F. transmitter of 13 to 15 db, exclude the possibility of jamming. (See Section IV.)

Difficulties with this proposed system are limitations in the rate at which one can communicate. This varies with what one is willing to spend, but the transmission rate is limited by the available bandwidth to 10 to 20 bits/second (or 20 to 40 words/minute). However, this relatively low rate of transmission should be adequate to convey important messages to overseas bases and to the fleet in general, besides the special application of communication with the Polaris submarines.

<u>Brief Description of the System</u>

All the components required to build the transmitter are already developed and being built in large quantities for other uses. Thus the most difficult and expensive components already exist and could be directly adapted for use. R & D is required however to improve the receiver.

Radiation of electromagnetic waves at these unconventional frequencies is to be achieved by exciting a huge area of several thousands of square miles as a slot antenna. In order to minimize power losses an area of poor ground conductivity, such as the conductivity of very old granite rocks, is required. It appears that the most attractive area in this respect (23,000 square miles) is located in Wisconsin.

The excitation is to be achieved by means of conventional transmission lines grounded at both ends at the perimeter of the excited area. It is proposed to use conventional Diesel locomotives as the source of prime power in a large number of (unmanned) stations, thus securing invulnerability by dispersion. (If one part of the web is knocked out the system as a whole suffers only partly.) The transmitter is to be installed in a passenger-type railroad car. Both the locomotive and the car are to be parked in reinforced concrete tunnels hardened to 1000 psi. A total of 310 stations and 10,000 miles of transmission lines are required to provide and convey the power to the antenna, which is designed to radiate 125,000 watts at 50 cps.

Evolution of the Idea*

In the summer of 1958 in a briefing given by the Polaris Special Projects Office, I became aware of the Navy requirement to communicate from CONUS to a deeply submerged submarine. It was emphasized that it was desirable not to encumber the submarine speed and

*Part of this sub-section appeared in "BASSOON III", Ref. (6).

freedom of maneuvering with trailing probes or buoys, etc. Needless to say, such communication should be free of jamming.

A week later it occurred to me that a very low frequency electromagnetic wave in the range 10 to 100 cps is the only method of communication which could meet simultaneously all the above requirements.

The original idea was to resonate the earth-ionosphere cavity at its natural modes. (At that time the existing information either of the Q of the cavity or the atmospheric noise level at this frequency range was very scarce. As a result, both the Q cavity and the noise level were estimated to be much higher than their actual value). A report(1) describing the BASSOON communication system in its original form was issued a few weeks following the Navy briefing.

A few months later a group of scientists with the participation of the Navy was invited to examine the proposed method of communication. The outcome of this study is summarized in a report(2) prepared by the Institute for Defense Analyses. The most important theoretical result of this study group was the discovery by K. Watson and V. Fitch(2) that the Q of the ionosphere in the frequency band below 1000 cps is constant, independent of the frequency. Therefore the attenuation along the wavepath is proportional to the frequency. This theory has been verified experimentally later on.

As a consequence of recommendations of this study group and the P.C.C.C. (Polaris Command Communications Committee) the Navy started an experimental program to measure the attenuation constant and the noise level. The first experiment consisted of energizing the Jim Creek antenna, radiating approximately one watt at the frequency range of 600 to 1000 cps.

The most important result of this experiment, concluded in the summer of 1960, was the measurement of the attenuation constant. The measured value of the daytime attenuation is:

$$\alpha = 1.7\left(\frac{f}{100}\right) \text{db}/1000 \text{ km} \qquad \text{(I.1)}$$

This in turn determines the Q of the cavity, namely Q = 5.67.

At the same time an elegant experiment was performed in the Lincoln Laboratory of M.I.T. For the first time the noise level at the frequency band 5 to 50 cps was measured. A pronounced peak at the lowest mode (10.5 cps) was observed. The frequency is shifted to 8 cps because of the low value of Q. A value of Q = 4 was measured at the lowest mode. The value of Q increased slightly up to a value of 6 at the fifth mode (40 cps). Therefore, these measurements in the two extreme ends of the E.L.F. band, both yielding substantially the same value of Q, verified Watson's and Fitch's theory. Since the value of Q turned out to be much smaller than I had assumed initially, communication by exciting the cavity modes proved not possible. A travelling wave can be employed instead.

The noise level measured by Balser and Wagner[3] in the Lincoln Laboratory was 75 db below one volt per meter in the range 20 to 50 cps. An enhancement of 6 db was observed at the cavity resonance of 8 cps as expected. Therefore during the summer of 1960 all the information about the physical parameters pertaining to the propagation, attenuation and noise level in the range of 10 to 100 cps was available. As a result it was possible to calculate the required radiated power as a function of frequency and transmission rate. Then it turned out that the antennae I had proposed in my first report(1) were too inefficient to radiate the required power. Hence the P.C.C.C. advised the Navy to drop the idea. I realized however that if more efficient antennae could be devised, communication at these unconventional frequencies would be practical. Then it occurred to me that if an electric field could be excited over a poorly conducting ground, the thus excited area would act as a slot antenna. If the area thus excited could be large enough (a few thousand square miles) it appeared that sufficient power could be radiated. The complete theory of the new antennae is described in a report (4) issued in August 1960.

A crucial question was whether or not there do exist in our country enough areas of poor conductivity to reduce the cost of an E.L.F. communication system to reasonable and acceptable levels. A search in the literature revealed a paper(5) by R. H. Card published in 1935. In this paper there was discussion of the correlation between the resistivity and the age of a variety of granites and gneiss rocks. It was observed that Pre-Cambrian rocks exhibit a very high resistivity ranging from 4,000 to 10,000 ohm meters.

An optimization process included in Ref. (4) yielded the conclusion that a system of E.L.F. communication in the range of 25 to 100 cps is feasible provided, however, that there do exist in our country enough areas (totalling 30,000 square miles) of average resistivity of 4000 ohm meters.

Following this conclusion I submitted the report to the Navy. An ad hoc committee was appointed early in 1961 to evaluate the proposal and design a crucial experiment to verify the radiation properties of the proposed antennae. At the same time a more intensive effort started towards measuring the atmospheric noise level in the frequency range of 25 to 250 cps.

By the fall of 1961 the experiment proposed by the ad hoc committee was approved. A 110 mile long line was constructed in North Carolina. The installation was completed by Christmas 1962. In January 1963 the antenna was excited with 50 amps A.C. in a number of frequency bands from 78 to 256 cps. Although the radiated power was approximately one watt, a signal of 0.01 cps bandwidth was successfully received in a submerged submarine (150 feet deep, 500 nautical miles from the transmitter) moving at a speed of 6 knots with a sensor mounted in the hull. Thus for the first time an electromagnetic signal was received by an unencumbered submerged submarine without the aid of a trailing buoy.

What remained, following the successful experiment, was to measure the ground conductivity of geologically promising areas and a practical design of the transmitter optimizing the cost of the proposed communication system. During the second half of 1964 I proposed a practical design of an E.L.F. transmitter[6], emphasizing invulnerability by dispersion. I suggested the use of a large number of unmanned stations built on trains and powered by Diesel locomotives. In the meantime conductivity measurements in Wisconsin indicated that Wisconsin is the most attractive area to build an E.L.F. transmitter. On the basis of the measured conductivity and the available area I designed the Wisconsin E.L.F. transmitter described in what follows.

Wisconsin as a Site

Since BASSOON III was issued, conductivity measurements have been analyzed and presented by DECO and RCA in a meeting at USNUSL on December 16, 1964. It turns out that the conductivity of the rock under Lake Superior is rather high, probably because of sediments. Consequently, Lake Superior is not suitable for E.L.F. antennae. The measurements in Wisconsin, however, confirmed DECO predictions that the conductivity is of the order of 10^{-4} mho/meter. The area of poor conductivity in Wisconsin, shown on the attached maps, is approximately 23,000 square miles.

In more detail the results were as follows:

	σ mho/meter	
Area	DECO	RCA
4400 sq. miles	$0.5 - 1 \cdot 10^{-4}$	$0.7 \cdot 10^{-4}$
19,000 sq. miles	$1 - 3 \cdot 10^{-4}$	$2 \cdot 10^{-4}$

The conductivity was measured by DECO in 10 different locations by the 4-probe method, surveying approximately 1000 square miles in each location. RCA measured the horizontal component of the conductivity only in two points at frequencies near the contemplated operation frequency.

The Wisconsin area, besides meeting the basic requirement of poor conductivity, offers three other advantages:

1. It is the only area of poor conductivity with flat terrain. Consequently the cost of the transmission lines will be less than in mountainous areas.

2. There are thousands of lakes and ponds, facilitating grounding the terminals of the transmission lines.

3. The center of the antenna area is located at approximately 45° N.L. and 90° W.L. As a result it is possible to cover all possible Polaris operational areas with one array of transmission lines pointing North-South.

Some Operational Features

The 10 db contour of an E.L.F. transmitter located in Wisconsin is shown in the map. A signal-to-noise ratio of 10 db is achievable at a transmission rate of 4 bits/second under the pessimistic assumption that the atmospheric noise is 72 db below one volt/meter. The radiated power is 125,000 watts at 50 cps.

Since the radiating area is limited to 23,000 square miles, a soft transmitter system is not invulnerable to nuclear attack. Therefore it is proposed to build the transmitter hard enough so that after a nuclear attack with a missile force equivalent to the total Polaris force on station, still enough elements of the transmitter will survive to transmit at a rate of 0.5 bits/second at 10 db signal-to-noise ratio. It has been assumed by SP204 that

DOE b(3)

that 400 to 500 bits are adequate for complete retargeting of a submarine, including instructions on the time of launch. [redacted] (b)(3) 42 U.S.C. 2011 et seq. [redacted] Therefore it is quite probable that the transmitter may not be attacked at all.*

All the required Polaris communications can be carried by the E.L.F. transmitter.** Then the submarines will be freed at last of the encumbrance of floating wires, V.L.F. buoys, etc., etc. The Polaris submarines will be allowed for the first time to use their superb performance in speed and maneuverability.

The transmitter consists of two arrays with 310 elements each. The power is provided by 310 unmanned stations, 1275 kw each. The stations are located inside tunnels of reinforced concrete with walls thick enough to stand an overpressure up to 1000 psi. It is proposed to build the elements of the arrays underground (cable buried 6 feet deep, 1000 psi hard).

As will be shown later, the cost of the transmitter, with two arrays to provide global coverage is estimated at $650 million. If the transmitter will be used exclusively to cover the Polaris operational areas, plus the areas shown within the 10 db contour in the attached map, then only one array is required, and the cost would be reduced to $500 million.

---

*Vulnerability discussed in Section IV.
**See Section following.

II. TRANSMISSION RATE & POWER (ANTENNA INPUT & RADIATED) REQUIREMENTS

The required radiated power of the transmitter has been calculated under the following assumptions.[6]

(1) The noise level at 50 cps is 72 db below one volt/meter at one cycle bandwidth. This level is 2 db more pessimistic than the level assumed by RCA[7] in calculating a hard transmitter with a transmission rate <u>0.25 bits/second</u> at an estimated cost of $500 million, and a signal-to-noise ratio of 10 db at 15,000 km range.

(2) The attenuation at 50 cps is 0.8 db per 1000 km.

(3) The ionospheric height at E.L.F. is 75 kilometers.

(4) The required 10 db (signal-to-noise ratio) contour at a transmission rate of 4 bits/second, i.e., a bandwidth of 4 cycles per second, is the contour shown in the map.

(5) The submarine self-noise is equal to the atmospheric noise at the depth of reception. Thus the overall noise level is 3 db above the atmospheric noise.

(6) The receiving antennae are mounted on the hull. By properly connecting the two electrostatic antennae, already successfully tested in a nuclear submarine, the figure 8 radiation pattern of the antenna can be pointed always toward

the transmitter. Thus the 3 db directivity gain of the receiving antenna offsets the submarine noise at the reception depth, as it is defined above.

The question may arise that, if a rate of transmission of 0.5 bits/second is an adequate one, why have I assumed 4 bits/second? There are three reasons for this assumption:

(1) Before a nuclear attack any instruction given to a submarine must exclude any error whatsoever. Therefore a very high signal-to-noise ratio is required. The BMEWS system operates at 17 db signal-to-noise ratio. The proposed transmitter will transmit information concerning orders to fire or to retarget at a rate of 0.5 bits/second at a signal-to-noise ratio of <u>19 db</u>, thus excluding any error and including a 2 db margin above the 17 db adopted in BMEWS. In a post-attack environment, however, if the E.L.F. transmitter is attacked with hundreds of missiles, it means that our country has been attacked with thousands of missiles. Therefore it is obvious that we are at war, and there is no need of 17 to 19 db signal-to-noise ratio. A reduction of the signal-to-noise ratio to 10 db means that one in every hundred missiles either will not be launched, because the information was not transmitted, or it will be sent to the wrong target. The latter is of lesser importance, however, after the United States has been attacked by thousands of missiles.

(2) A transmission rate of 4 bits/second provides in addition:

(a) 8 words*/minute at 99% probability of reception.

(b) 16 words/minute at 97% probability of reception.

(c) 40 words/minute at 95% probability of reception ,

from a limited vocabulary of 4000 words. This high transmission rate will allow the transmission of the RATT broadcast of entertainment, general news, messages to the crew, etc.

(3) The reception of an "alert signal" that a message is about to be received by "ringing the telephone" of a particular submarine while traveling at 22 knots at 350 feet keel depth. Then the submarine will ascend to 250 feet depth and reduce its speed to 10 knots to receive the message.

Under the above assumptions the required radiated power at 50 cps is

$$W_R = 125{,}000 \text{ watts}$$

The available transmitter area (F) is 23,000 square miles. This area will be excited as a slot antenna. The surface electric field is given by the equation (IV-3) of reference (6), namely

---

* I assumed a digital system: 5 bits per character, 6 characters per word.

$$W_R = \frac{(E_o F)^2}{480\lambda h} \quad \text{watts} \qquad \text{(II-1)}$$

where E_o is the RMS value of the surface horizontal electric field over the radiating area F, λ, and h are the wavelength and the height of the ionosphere, respectively, in kilometers, and F is the radiating area in square kilometers.

Substituting in equation (II-1), h = 75 km, λ = 6000 km, F = 59,500 sq km, and W_R = 125,000 watts, we find

$$E_o = 87.4 \text{ volts/km}$$

The power loss in a uniformly illuminated ground of conductivity σ is

$$W_o = (\sigma\ \delta\ E_o{}^2/2) \text{ watts/km}^2 \qquad \text{(II-2)}$$

where σ is the conductivity in mho/km and δ is the skin depth in km.

In order to be on the conservative side, I have assumed the following values of conductivity in the area of 23,000 miles where it is proposed to build the transmitter.

TABLE I

Area	σ(mho/km)	δ_{km}	W_o(kw/km^2)	W_{tot}(kw)
4000 sq miles (10,300 sq km)	0.1	7.07	2.7	27,800
19,000 sq miles (49,200 sq km)	0.24	4.55	4.17	205,200
		Total Ground Losses		233,000 kw

The ground losses listed in the table are correct for the ideal case where the 23,000 sq miles slot antenna is uniformly excited with a surface electric field E_o = 87.4 volts/kilometer. Because of the concentration of current under the transmission lines which energize the slot, the above ground losses are enhanced by a factor (F_g) depending on the distance (D) between transmission lines. The theoretical derivation of the additional losses is discussed in Ref. (4). The percentage increase (F_g) of the losses as a function of (D/δ) is listed in the following table.

TABLE II

(D/δ)	F_g%
0.5	1.5
1.0	7.0
1.5	18.0
2.0	33.0

We observe that the ground losses increase rather rapidly for values (D/δ) larger than 1.5. The optimum solution is obtained when the cost of the transmission lines (excluding the conductor cost) is equal to the cost of the additional transmitter power required to compensate the additional power loss shown in Table II.

The size of the copper conductors in the transmission lines is optimized when the cost of the conductors installed is equal to the cost of the transmitter power required to compensate their ohmic losses. The optimization procedure is discussed in the next section.

III. DESCRIPTION OF THE TRANSMITTER OPTIMIZED FOR COST

It is proposed to build the stations on trains, powered by Diesel electric locomotives. A Diesel electric locomotive costs approximately $83 per brake horsepower. The type which currently is produced in large numbers (several hundred per year) is 2500 horsepower. The output of the generator is approximately 1900 kw. It is possible to operate continuously Diesel locomotives at 75% of their peak power. Thus at 75% of the peak power the generator output of the standard (2500 horsepower) locomotive is 1425 kw.

The D.C. output of the locomotive's generator will be inverted to A.C. at 50 cps with ignitron-inverters. The unit cost of the ignitron-inverters is $190/kw according to Ref. (8). In this price is included the cost of the tuning condensers and the output transformer which couples the power to the transmission lines. It is proposed to park the trains in reinforced concrete tunnels (Figs. 1,2) with walls five feet thick, they would thus be capable of withstanding an overpressure (from a nuclear explosion) up to 1000 psi. Fuel tanks will be provided within the tunnel for one month fuel storage. The output transformer for each of the two elements, which each station is energizing, is installed in the tunnel as well as the tuning condensers. The ignitron-inverters, 1275 kw per station, can be installed in one passenger car. The output of the ignitron-inverters can be coupled to the output transformer through two "third rails," as it is done in electric railroads. By properly apportioning the power to each output transformer, thus to each of the two elements of the array, it is possible to rotate the radiation pattern of the slot antenna to any desired direction.

The cost analysis of each station is shown in Table III.

TABLE III

One 2500 hp Diesel locomotive		$207,500
One passenger-type railroad car		$140,000
Ignitron-inverters, 1275 kw @ $190/kw		$242,500
Communications from and to main control stations		$ 40,000
		$630,000
Reinforced concrete tunnel 3000 c.y. @ $65/c.y.	$195,000	
Steel door	$ 25,000	$220,000
		$850,000

I have assumed 20% reserve stations ready to replace defective ones or undergoing maintenance. The cost of the reserve stations brings the total cost per operating station to $976,000 or $765 per kw of transmitter power. In order to optimize the cost of the transmitter we shall derive the array cost. It is proposed to build the arrays underground.

The underground elements of the array are visualized as single copper cables, 500,000 cir. mils, insulated for 10 KV, 60 cycles, continuous operation.

The cost of the underground section of the array is estimated as follows.*

TABLE V

Right of way acquisition	$2,500/mile
Right of way surveying, mapping and clearing	3,250/mile
Trenching (6 feet) and backfilling	7,500/mile
Selected fill and protective barrier	2,500/mile
Cable installation	750/mile
Total (excluding cable)	$16,500/mile

Cable	5000 volts	500,000 cir. mils	$ 7,500/mile
"	" "	1,000,000 " "	$12,500/mile
Cable	25,000 volts	500,000 cir. mils	$20,000/mile
"	" "	1,000,000 " "	$33,000/mile

In the proposed installation the length of the elements do not exceed 20 miles. Therefore a 6 KV cable is adequate. Providing for future power increase, however, and better protection from an induced emf by the E.M.P. generated by a nuclear explosion, I have assumed a 10,000 volt cable. The cost of the 10,000 volt cable is derived from Table V by interpolation.

* Information provided by Dr. Q. Powers, RCA, private communication.

Cable	500,000 cir. mils	\$11,000/mile
"	1,000,000 " "	\$18,000/mile

The total length of the elements of the two arrays and their cost as a function of (D/δ) are listed in Table VI. In columns 4 and 5 are listed, respectively, the additional ground losses as a function of (D/δ) and the corresponding cost of the transmitter (@ \$765/kw) required to provide this power.

TABLE VI

(D/δ)	L(Miles)	Cost (in Million \$)	Additional Ground Losses (kw)	Transmitter Cost (Million \$)
1	15,240	251.5	16,300	12.47
1.5	10,160	167.6	42,000	32.13
2	7,620	125.7	77,000	58.9
	Difference	-41.9		+26.8

The transmission line current, and the power losses in the conductors as a function of (D/δ) are shown in Tables VII and VIII in two cases, respectively:

(a) Underground cable 1,000,000 cir. mils

Resistance R_e = 0.055 ohm/mile

(b) Underground cable 500,000 cir. mils

Resistance R_e = 0.11 ohm/mile

The cost of the conductor installed and the cost of transmitter power required for the ohmic losses of the conductors are listed in columns 3 and 4 of the following tables:

TABLE VII

(D/δ)	I (amperes)	W_c(kw)	Conductor Cost (in Million $)	Transmitter Cost (in Million $)
1.5	463	60,000	182.9	41.7
2.0	618	80,000	137.2	55.7
Difference			-45.7	+14.0

TABLE VIII

(D/δ)	I (amperes)	W_c	Conductor Cost (in Million $)	Transmitter Cost (in Million $)
1.5	463	120,000	111.8	83.4
2.0	618	160,000	83.8	111.4
Difference			-28.0	+28

From the above tables we conclude that the cost is practically the same for three cases which are summarized in Table IX.

TABLE IX

(D/δ)	Q	R_e(ohms/mile)	Total Power Loss (kw)	Station Cost	Array Cost	Total Cost
1.5	4.5	0.11	395,000	302.2	279.4	581.6
2.0	4.8	0.11	470,000	359.6	209.6	569.2
2.0	6.0	.055	390,000	298.4	262.9	561.3

We observe that in the first and third cases the total transmitter power is the same. The additional ground losses are offset by the smaller conductor losses. The total difference in cost is insignificant to constitute a decisive factor. In my opinion the first case is preferable for two reasons:

(a) The Q is somewhat smaller, thus allowing a 25% larger bandwidth.

(b) The line current is smaller, thus reducing interference in the neighborhood of the transmission lines.

The second case requires more power. Thus although the initial investment is smaller, this small difference will be offset by the fuel costs in 5-year operation. Therefore the proposed design of the transmitter is to install the lines (1.5 δ) apart and to use 500,000 circ. mils cables. The total cost of the system is:

10,160 miles underground cable @ $27,500	=	$279.4	M
310 ground connections @ $50,000	=	15.5	M
Total array cost		$294.9	M
310 stations @ $850,000	=	263.5	M
60 reserve stations @ $630,000	=	37.8	M
		596.2	
Miscellaneous, contingency		53.8	
Total transmitter cost		$650.0	M

It is of interest to compare the results of the above optimization with the parameters derived by the optimization procedure described in Ref. (4) and employed in Ref. (6). According to the old optimization $(D/\delta) = \sqrt{2}$, the total length of lines L = 10,780 miles, and the required number of stations is 300. The cost of the system is $604 million. Consequently it is obvious that the more sophisticated optimization procedure employed in this report resulted practically in the same cost.

The general pattern of the arrangement of the stations is shown in Fig. 3. The length of each element is 16.4 miles. The distance between adjacent lines is 6.59 and 4.24 miles respectively, in the low (4000 sq. miles) and high (19,000 sq. miles) conductivity areas.

Each half element consists of 8.2 miles of underground cable. Each element is connected to the next one, but the connection is grounded. In this way if the elements are in phase there is no ground loss at the end of each element except at the perimeter of the energized area of 23,000 square miles. As a result, the terminal connection resistance, averaged over the length of each element, is approximately 0.003 ohms/km. Differences in amplitude, however, between adjacent elements, may cause a fraction of the line current to return through ground connections in the middle of the array. Even if the current in these ground connections is as high as 20% of the line current (463.5 amperes), the total ground connection losses will be doubled. Thus I finally assumed a ground connection resistance 0.006 ohms per km.

The total resistance of the element's circuit per km is

Ground resistance R_g		=	0.157 ohm/km
Line resistance R_e		=	0.068 ohm/km
Ground connection resistance r_g		=	0.006 ohm/km
Total	R	=	0.231 ohm/km

The combined line-ground return reactance of the arrays is 1.044 ohm/km (at 50 cps). Thus the Q of the system is 4.50. The allowed bandwidth is 11.0 cps. Consequently the maximum rate of transmission is 10 bits/second.

IV. RESISTANCE TO NUCLEAR ATTACK

The philosophy behind the design of this hardened and dispersed transmitter system is that the enemy would find small value in attacking it at all if the number of missiles required to destroy the usefulness of the system were larger than our total Polaris force on station.

In order to estimate the vulnerability of the transmitter, i.e., its post-attack transmission rate, as a function of the number of missile hits it absorbs, I assumed a range of pre-attack transmission rates and then studied the effect of increasingly severe attacks in these various initial transmission rates. The rule I adopted for an attack was to assume that each enemy missile carries a single one-MT warhead, and has a C.E.P. of one-quarter of a nautical mile (expected 5 to 6 years hence). The 1000 psi range of a one-MT warhead is approximately 0.25 nm. I assumed each station in the transmitter net to be hardened to 1000 psi and hence the probability of survival of each station in the transmitter net against an attack is 50% for each missile arriving on target.

The underground transmission lines are also hardened to 1000 psi, but, because they are long targets, the probability of survival against one-MT warheads at 0.25 nm C.E.P. is 25%. There are two half-elements per station in each direction, however. Therefore two missiles hitting off station but aimed at the transmission lines will destroy both half-elements with a probability of 75%, but leave intact the other two half-elements. If the same warheads hit the station, they have the same probability (75%) of destroying the station, thus rendering useless all four half-elements associated with the station. Therefore it appears that it is more profitable for the enemy to aim his missiles at the stations rather than at the elements. But notice, if a missile aimed against a station lands at a distance larger than one-quarter of a mile from the station but closer than 0.25 to the elements associated with the station, it may destroy one half-element. In order to avoid this possibility the stations are designed to be installed at a distance of approximately one mile from the intersection of the two elements of the array, and then to feed the lines through two different cables. This secures survival of the connection between the station and the elements even if one feed is destroyed. In this way the weakest components are the stations themselves. Hence in what follows, the survival of the system will be calculated as a function of the survival of the stations.

The probability of the survival of N stations is

$$N = N_s \exp (- 0.7N_m/N_s) \tag{IV.1}$$

where N_m is the exploded number of missiles and N_s the total number of stations. As the number of stations are substantially decreased, more elements will become isolated. As a result the resistance of the element's circuit will become higher because the terminals of each element will be grounded independently. I assumed that the resistance of each terminal grounded in a lake is 0.1 ohm, and if it is grounded on land I assumed a resistance of 1 ohm, and that one out of three groundings will be on a lake, thus resulting in an average resistance of 0.7 ohm, or 1.4 ohms per element. The calculations of radiated power are based on a total resistance of 6 ohms/element. Thus the radiated power is asymptotically reduced by 20% as all the remaining elements tend to become isolated.

The radiated power is proportional to the square of the number of stations. Consequently the post-attack rate (R) as a function of the pre-attack rate (R_o) is

$$R = \alpha R_o \exp(-1.4\, N_m/N_s), \qquad \text{(IV.2)}$$

where

$$\alpha = 1 - 0.2\, [1 - \exp(-1.4\, N_m/N_s)\,]. \qquad \text{(IV.3)}$$

The quantity α provides a correction to the radiated power which would result from the increase of grounding resistance of the elements as they become isolated because of the destruction of neighboring stations.

In the following table are listed the values of (R/R_o) and the other pertinent quantities for N_s = 310 stations, as a function of the number of arriving missiles N_m. The survivability has been calculated as straight probability, not taking into consideration the possibility of enemy post-attack reconnaissance.

With the aid of the table one can calculate the survivability for any given initial number of stations. I have calculated the post-attack rate for different pre-attack rates, namely in the range 0.25 - 8 bits/sec pre-attack rate. In the range of 0.25 - 4 bits/sec I assumed that both the number of stations and the covered area is

N_m	(N_m/N_s)	$\exp(-1.4\, N_m/N_s)$	α	(R/R_o)	R^* bits/sec
50	0.161	0.798	0.960	0.766	3.1
100	0.323	0.636	0.927	0.590	2.4
200	0.626	0.416	0.883	0.368	1.5
300	0.968	0.258	0.852	0.220	0.88
400	1.29	0.164	0.833	0.137	0.55
500	1.61	0.105	0.821	0.086	0.34
600	1.93	0.067	0.813	0.054	0.22
700	2.26	0.042	0.808	0.034	0.14
800	2.58	0.027	0.805	0.022	0.09

proportional to the square root of the rate. In the range of 4 to 8 bits/sec I assumed that the total available area in Wisconsin is covered by the transmission lines (10,160 miles of underground cable, covering 23,000 square miles) and that the number of stations increase linearly with the rate of transmission. Finally I assumed that the cost is

$$C = 300\, R_o^{\frac{1}{2}} \text{ million dollars.} \qquad \text{(IV.4)}$$

Equation (IV.4) yields a cost of \$600 million for R_o = 4 bits/sec, which is the cost calculated in Section III. In this cost is not

* for R_o = 4 bits/sec

included the 10% contingency nor the 5-year operational costs.

Under the foregoing assumptions two sets of curves have been prepared (Figs. 4 and 5). In Fig. 4 the transmission rate in bits/sec is plotted as a function of the initial investment for several magnitudes of attack. In Fig. 5 the required initial investment is plotted as a function of the magnitude of the attack for three cases of post-attack transmission rate, i.e., 0.1, 0.5 and 1 bit/sec.

We observe that with the design proposed in this report ($600 million initial investment plus contingency) the desired 0.5 bit/sec post-attack rate is maintained even after a heavy attack with 450 one-MT warhead missiles, i.e., a force approximately equal to a Polaris force on station. In order to maintain the same post-attack rate for heavier enemy attack, the required increase of initial investment is $600,000 per expected additional enemy missile, or approximately $800,000 if we include the cost of 5-year operation. A similar missile costs us, however, approximately $5 million for 5-year operation. Therefore we may conclude that the exchange ratio is so unfavorable for the enemy that the station, if built as hard as is proposed, may not be attacked at all. The cost of the transmitter for 0.5 bit/sec, pre-attack rate, is $200 million. Thus with an additional $400 million we can secure the same rate after an attack with 450 missiles costing much more than $400 million.

According to my reasoning, if a station is built this way the additional $400 million cost should be considered as invested in two different ways, depending on whether or not the enemy will attack the transmitter.

(1) If the enemy indeed attacks the station with 450 missiles, then the stations can still accomplish its Polaris communications mission and we would have diverted 450 one-MT missiles at a cost of the order of $1 million per missile, which is a very inexpensive ABM indeed.

(2) If the station is not attacked we would have acquired an invulnerable transmitter which, besides its Polaris mission, can transmit for surface-surface communications 16 words/minute at 7 db signal-to-noise ratio omnidirectional or 10 db in a directional pattern, or 40 words/minute from a limited vocabulary of 4000 words. At a time where all the V.L.F. stations will have been destroyed as well as most other communications, such a station will be a very valuable means to secure communications, even at its low rate, at any location in the globe.

V. RESISTANCE TO JAMMING

The proposed ELF communication system is inherently very resistive to jamming. In contrast to any other rf transmitting systems mobile ELF stations cannot be built because an ELF transmitter is a large installation which requires special geological conditions to radiate efficiently. This also means that it cannot be built at just any desired location in USSR or China and this in turn means that its possible location can be predicted by studying geological maps. There is some indication that such a possible location exists in Kasakhstan (USSR) near the Aral Sea. Since an ELF transmitter is a large installation it cannot be built overnight. Therefore the construction of the transmitter will be observed well in advance to allow relocation of the operational areas which may be affected by the prospective jammer.

The 10 db contour shown in the attached map encircles completely the Eurasion continent and so there is a large selection of POLARIS operational areas to which ELF communication is feasible. An enemy jammer can cover, at the most, only some particular areas. What counts in the presence of jamming is not the radiated power but the received power density (watts/m^2) at the receiver site. The propagation loss of an ELF wave is less than one db/1000 km. Therefore the location of a jammer at a smaller distance from the receiver than our ELF transmitter is not as dominant a feature in its capability of jamming as it would be at higher frequencies.

The received power density of an ELF wave at a distance D from the transmitter is

$$w_e = \frac{W_R}{\pi D h}\left(\frac{\varphi}{\sin\varphi}\right)\left(\sin^2\theta\right)\left(\sin^2\psi\right) e^{-\alpha_e D} \text{ watts/km}^2 \qquad (V.1)$$

where W_R is the radiated power in watts, $\varphi = (D/a)$, a is the earth's radius, h is the ionospheric height, θ is the angle between the direction of the receiver and the direction of maximum radiation intensity of the transmitter, ψ is the angle between the direction of maximum gain of the receiving antenna and the direction of the transmitter and α_e is the attenuation constant, namely

$$\alpha_e = 3.7 \cdot 10^{-4} \left(\frac{f}{100}\right) \text{km}^{-1} \qquad (V.2)$$

In the described ELF transmitter two arrays of antennae are provided. By proportioning the power in the two arrays it is possible to obtain maximum radiation towards any desired direction. Therefore in the following calculations I assumed that $\sin^2\theta = 1$.

It appears that it may be feasible to build a directive receiving ELF antenna. A pair of electrostatic antennae mounted in the hull of a submarine have been successfully tested. This pair of antennae was intended to provide omnidirectional reception. It appears feasible, however, to create the familiar figure 8 pattern of a loop by properly mixing the signals received in each antenna, and rotating the lobes (of the figure 8 pattern) towards any desired direction. Thus it is possible to turn the null of the receiving antenna towards the enemy jammer.

In order to evaluate the resistance to jamming of the proposed ELF transmitter we shall assume as an example a particular location and the radiated power of the enemy jammer. A convenient assumption is that the radiated power is equal to that of the proposed Wisconsin transmitter. As an example I selected a jammer location 2500 km north of Karachi, Pakistan which is approximately 2500 km N.E. of the East Mediterranean operational area.

The signal to jammer ratio is

$$\frac{W_s}{W_j} = \frac{(\sin\varphi)_j}{(\sin\varphi)_s} \cdot \frac{(\sin^2\psi)_s}{(\sin^2\psi)_j} \exp < -\alpha_e (D_s - D_j) > \qquad (V.3)$$

The transmission rate R, in bits per second under the assumption that a 6 db signal to jammer ratio is acceptable is

$$R = .25\ (\Delta f)\ (W_s/W_j)\ \text{bits/sec} \qquad (V.4)$$

where (Δf) is the bandwidth of the transmitter. The allowed data rate in East Mediterranean and Arabian Sea (500 km. south of Karachi) under the assumption that $f = 50$ cps and $(\Delta f) = 11$ cps are:

a. East Mediterranean

Distance to the transmitter $D_s = 9500$ km

Distance to the jammer $D_j = 2500$ km

Angle between the direction of transmitter and the direction of jammer $\psi_s - \psi_j \approx 60^o$

Then if $\sin^2\psi_s = 1$, $\sin^2\psi_j = .25$

$$R = 1.2 \text{ bits/sec}$$

which is higher than the desired ratio of .5 bits/sec

b. Arabian Sea

Distance to the transmitter $D_s = 12{,}500$ km

Distance to the jammer $D_j = 3{,}000$ km

Both transmitter and jammer are located practically on the same great circle. Thus a directive receiving antenna is not useful in this case. The allowed data rate is

$$R = .23 \text{ bits/sec}$$

The above calculations indicate that an enemy jammer of equal cost and power as the proposed ELF transmitter it will force us to reduce the desired data rate, in one of many possible operational areas, by a factor of two. There is no reduction of the performance of the system in all the other areas. Therefore in view of the foregoing calculations showing the ineffectiveness of an enemy jammer, it is very doubtful whether the enemy will ever attempt to jam the proposed ELF transmitter. Therefore one can conclude that for any practical purpose the proposed ELF communication system is invulnerable to jamming.

VI. REQUIRED STUDY, PROBABLE COMPLETION TIME, REMAINING R & D

It seems to me that recently there has been some misunderstanding about the R & D required before it is sensible to start building an E.L.F. transmitter. In my opinion, there is no research and development at all required in order to build an E.L.F. transmitter. The reason is that all the "building blocks" of the proposed transmitter are elements of power engineering which have been developed to perfection, for they are used in very competitive industries.

The "building blocks" of the proposed transmitter are:

1. Diesel-locomotives. The Diesel locomotives have been developed to perform very reliably. More than 10,000 have been built the last 20 years.

2. Ignitron-inverters. The principle was published in the literature more than twenty years ago. The equipment was developed initially to make possible the use of D.C. for transmission of electric power at long distances. There are a few D.C. power transmission lines in Sweden, built by A.S.E.A., and there is some thought about building such a line in California in the near future. Another application is in charging the magnet of high energy particle accelerators. Two accelerators at Brookhaven National Laboratory and

one at Lawrence Radiation Laboratory at Berkeley use ignitron-inverters (approximately 50,000 kw peak power, 10,000 kw average power) to transfer energy from a flywheel to the accelerator magnet. In this application the ignitrons operate both ways. They rectify A.C. to D.C. and charge the magnet up to its maximum current. Then the energy stored in the magnet is converted back to A.C. by operating the ignitrons as inverters. Two of these installations have been in operation for over ten years. Thus there is large experience on their operation and reliability. Any faults in their operation were rectified a long time ago. In the proposed application for the E.L.F. transmitter there is a new requirement, however. The phase of the A.C. must change periodically, sometimes as fast as every 100 milliseconds. This requirement, however, is rather a detail. Thus a contractor who may be the lowest bidder to build 3000 to 4000 identical units should be able to include the required minor development in the fabrication cost.

3. Transformer and tuning condensers. Conventional 60 cycle, cosϕ correction condensers and 60 cycle power transformers, which have been developed to perfection a long time ago, can be employed in the proposed transmitter without further development.

4. Buried cables. There exists a large variety of non-shielded cables adequate for buried operation.

The detail design of the transmitter, the distance between elements and the length of each element depend on the ground conductivity. An accurate mapping of the ground conductivity of the proposed area in Wisconsin could be obtained in the next six months if such measurements can start early in the Spring. By the end of the Summer the results can be analyzed and soon thereafter a detailed design and cost estimate of the transmitter can be prepared.

In my opinion the capacity of our industry is large enough so that it is possible to build the Diesel locomotives and the ignitron-inverters in two years. The elements of the array can be built in a year following acquisition of the land. Thus by the end of fiscal year 1967 the transmitter could be in the testing stage. By the end of calendar year 1967 the transmitter can be operational at full power, provided, however, that a decision will be made by the Navy in the next two or three months to proceed.

The question then arises where is it required to do more research and development, as it has been proposed recently? There is a lot of R & D to be carried out to improve the receiving conditions. During the last two years it was possible to reduce the noise in certain nuclear submarines by 20 db. Although further reduction of the submarine noise is a desirable goal, the receiving conditions discussed in Section II are based on present noise levels. For example, if another 10 db reduction can be achieved, normal reception at 400 feet at a speed of 22 knots may be feasible. A number of experimental receivers have been already built. There is no technological breakthrough required to build the receiver. In my opinion, there are many electronic industries which can develop and deliver operational receivers in two years. Another area of R & D is to devise and test a variety of geometries and materials for the receiving antennae.

Because there is some ambiguity in the atmospheric noise level, the height of the ionosphere and the attenuation constant, I have assumed the most pessimistic values of these natural constants. It is quite probable that the actual values of these constants are smaller, thus allowing the proposed transmitter to transmit simultaneously in both directions, securing a simultaneous global coverage. I don't know of any research which will improve the existing natural constants. It is our knowledge of these constants which will be improved by future research. But it should be clarified at this point that the invulnerability of the transmitter to nuclear attack has been examined under a postulated C.E.P. of one-quarter of a nautical mile. It is not expected, however, that this C.E.P. can be achieved before 5 to 6 years. Consequently there will be a margin in the transmission rate during the first 2 to 3 years of operation. During that time if, unexpectedly, the natural constants prove even more pessimistic than I have assumed, there will be enough time to increase the radiated power by 40 to 60 percent with an expenditure of $100 to 150 million.

Therefore, in conclusion, I would like to say that all the necessary information required by the Navy to arrive at a decision whether or not to proceed on E.L.F. is available today.

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Shaded Portion Shows Area of Poor Conductivity in Wisconsin

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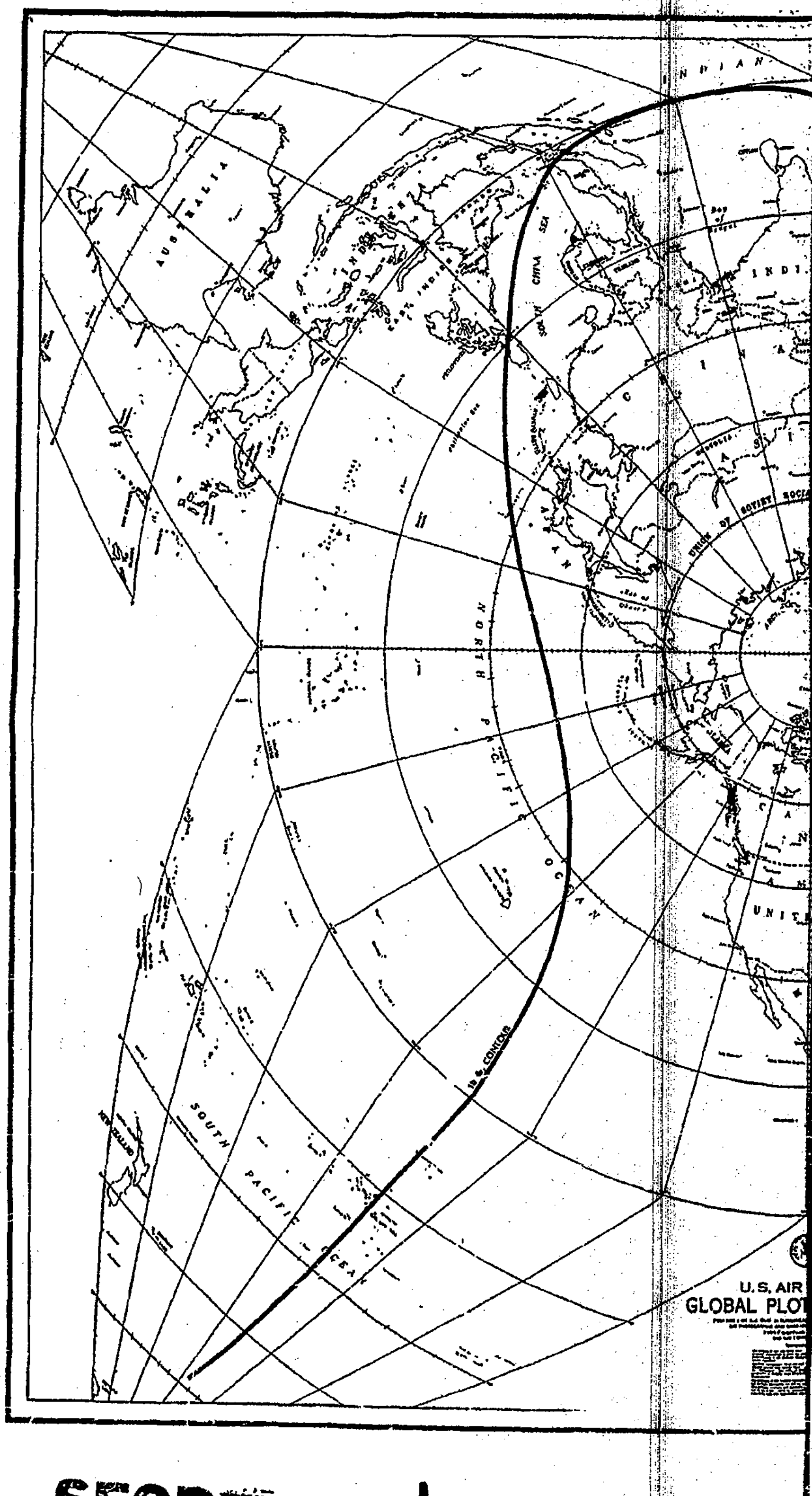

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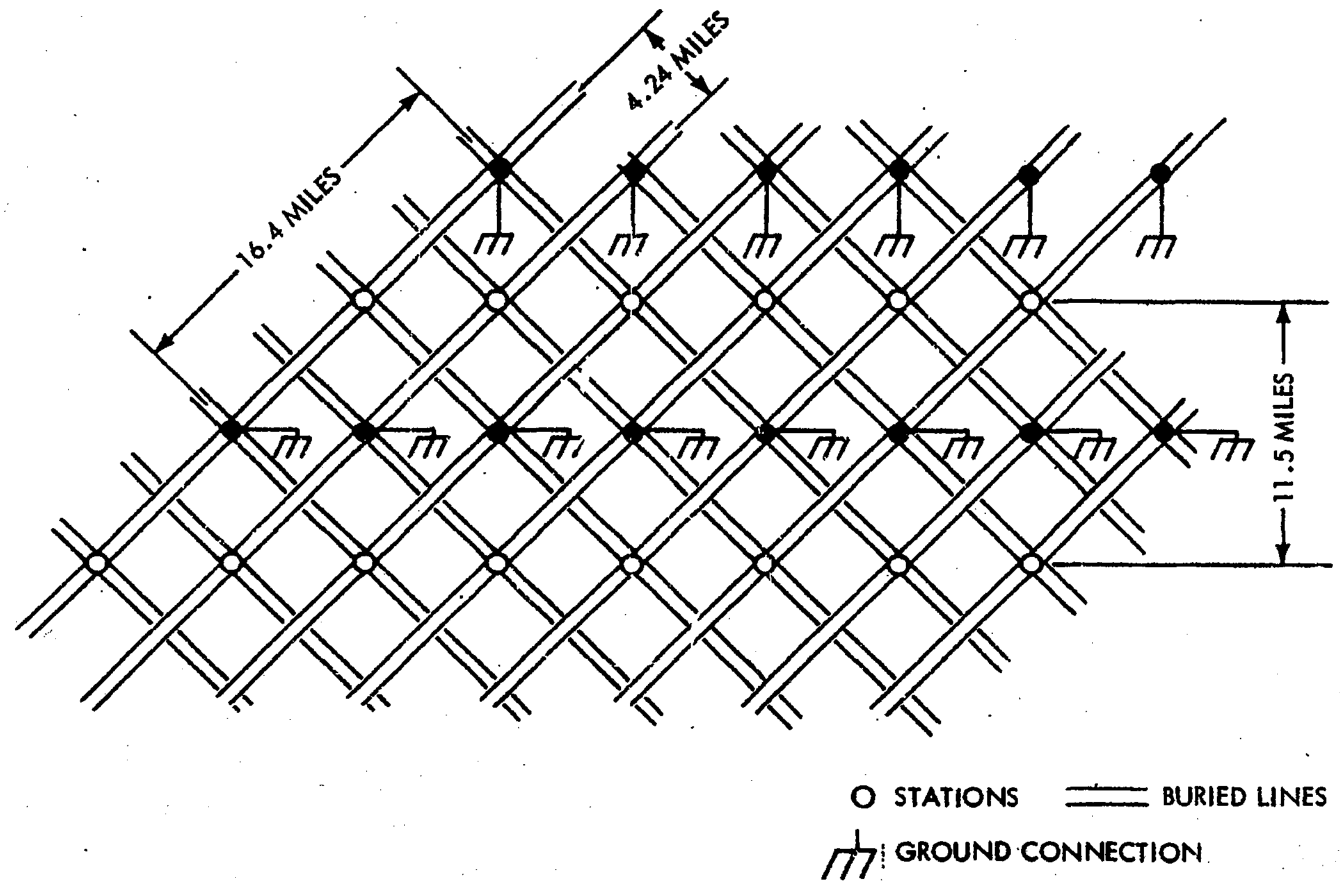

FIGURE 3. Layout of the Antenna Elements

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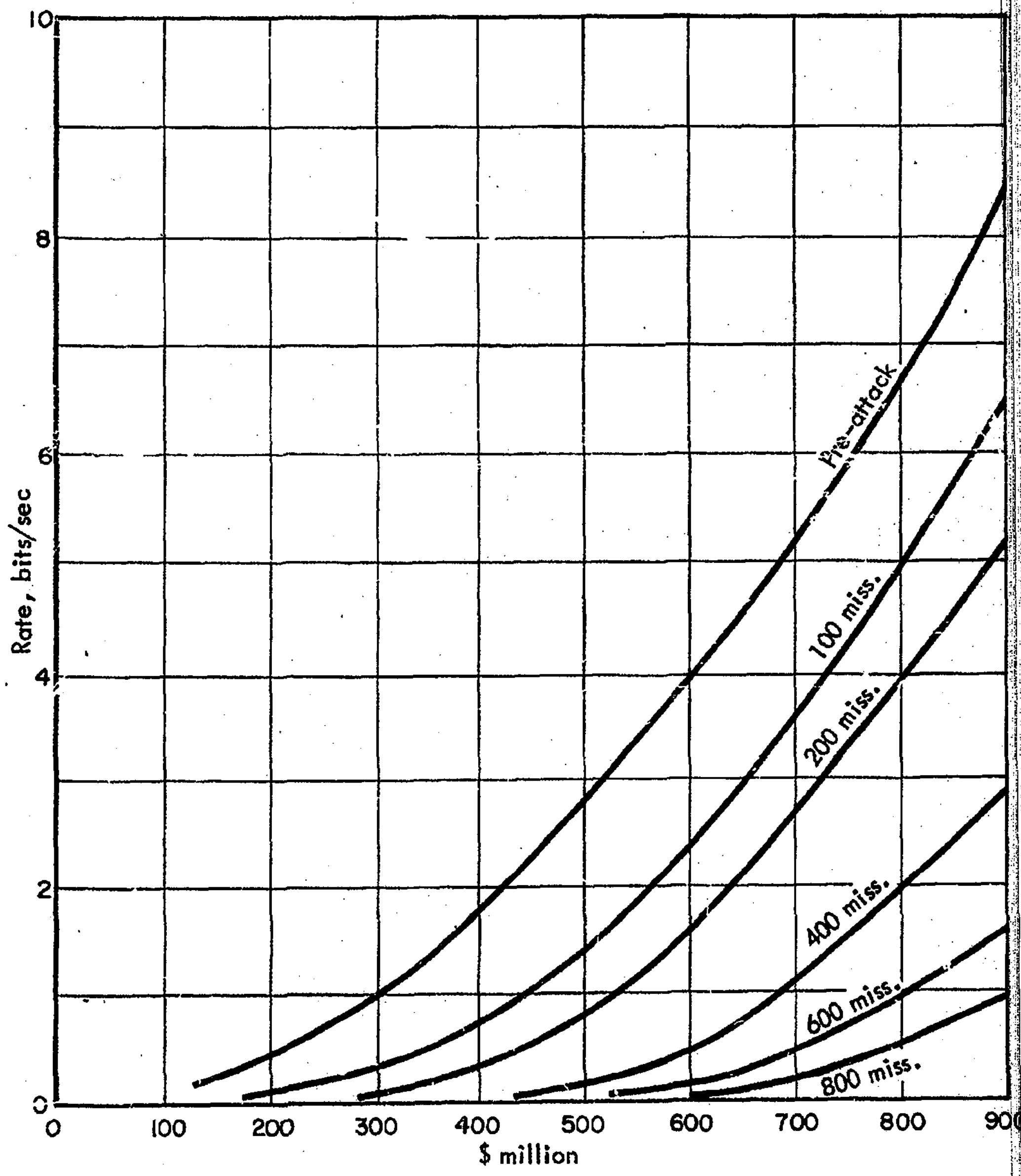

FIGURE 4. Post Attack Rate as a Function of Initial Cost for Various Attacks

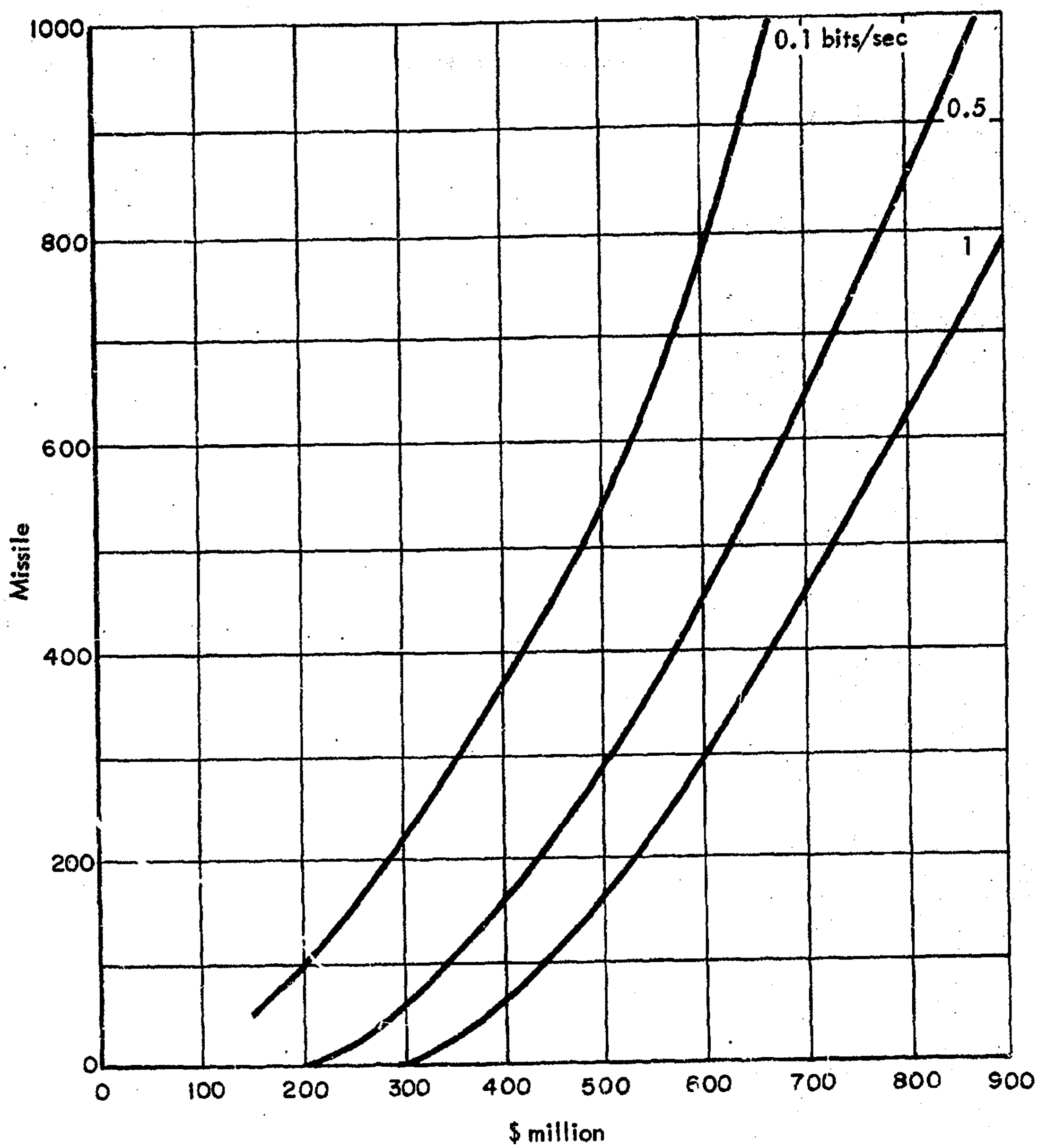

FIGURE 5. Initial Cost as a Function of the Magnitude of the Attack for Several Post-Attack Rates

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